Solar Tsunamis:

Space Weather Prediction and Risk Mitigation for New Zealand's Energy Infrastructure

EEA Conference & Exhibition 2021, 30 June - 1 July, Wellington

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Abstract

The 2017 United Nations Space Weather Thematic Report recognised the space weather hazard for its potential catastrophic global impact to the energy infrastructure, in particular the electrical power networks. Managing this type of hazard requires synergy and promotion of shared space weather interests by all stakeholders. An extreme storm is likely to produce a collapse of the electrical power grid with damage to the infrastructure and loss of service. The flow-down impacts are likely extreme, including extensive damage to property and infrastructure, as well as loss of life. While this is a comparatively new hazard, New Zealand core energy players are well aware of the risk.

Led by Professor Craig Rodger (University of Otago) we are undertaking a 5 year research programme investigating space weather impacts on key infrastructure. Both Transpower Ltd and the nation's largest gas pipeline operator, First Gas Ltd, are partners in this research proposal. Independently, with major shared objectives, they have identified the most crucial issues for NZ in this field of hazard mitigation research. To address these knowledge gaps, the research team has developed a Research Plan comprising a set of interlocking work packages outlined below.

- WP1: How likely is an extreme geomagnetic storm impacting New Zealand? What would this storm be like?
- WP2: What is the electrical resistivity structure of New Zealand?
- WP3: How do we predict the changing magnetic field across New Zealand during geomagnetic storms?
- WP4: Build and validate a 3-D GIC physics-based model for New Zealand.
- WP5: What forecasting and nowcasting tools can we provide to New Zealand industry operators?
- WP6: What is the incremental impact on many geomagnetic storms on core electrical infrastructure?
- WP7: How will New Zealand's natural gas pipeline protection systems be impacted by an extreme space weather event?
- WP8: Maximise the public awareness through outreach.

This paper will provide an overview of the planned research and how it is applicable to the New Zealand electricity industry.

1. Introduction

Electricity's role in a modern society cannot be overstated. Since the wide scale adoption of electricity, developed nations have grown in wealth and prosperity. A study by Ferguson et al. [1] of the relationship between electricity use and economic development in over one hundred countries, constituting over 99% of the global economy, found that wealthy countries have a stronger correlation between electricity use and wealth creation than do poor countries and that, for the global economy as a whole, there is a stronger correlation between electricity use and wealth creation than there is between total energy use and wealth.

The operation and maintenance of electrical networks is a complicated and expensive task and ensuring the reliable operation of the electricity system is the primary role of the System Operator. Large scale blackouts have major direct, and indirect consequences for the economy and national security. Though large cascading blackouts in the power transmission system are relatively rare, their impact is such that understanding the risk of large blackouts is a high priority [2] [3].

Risks to the security of supply are many and varied and include both natural and man-made hazards. It is important that sufficient planning is in place to meet these hazards and in the case of natural disasters such as earthquakes, volcanic eruptions and flooding the effects can be far reaching. To a certain extent in New Zealand, plans are well advanced to manage these natural disasters however, recently the potential effects space weather or large solar storms has been gaining a lot of interest in the literature. The potential consequences of a large event are far reaching with some estimates predicting multi-year power outages and costs in the trillions of dollars [4] [5].

In this paper, we outline what space weather is, how it translates to geomagnetically induced currents (GIC) and their effect on the electric power system generally and specifically in a New Zealand context. This is followed by an explanation and overview on how a multi-year, multiple research institute, government funded research programme will aim to better understand and mitigate the risks posed by space weather events.

2. So what are Solar Storms and why do we care?

The research field of space weather is all about the Sun-Earth relationship. The Sun is not solid but has an atmosphere that consists of charged particles and embedded in that atmosphere is the Sun's intense magnetic field. The output form the Sun is more than just light (Figure 1). It emits x-rays which travel at the speed of light and arrive at Earth in approximately 8 minutes, solar energetic particles (SEP) (80% speed-of-light ~30 minutes to 1-2 hours) in the form of higher energy electrons and protons, and the solar wind and associated magnetic field (average velocity of 400km/s, ~ 36 hours and as little as 16 hours). The Sun's atmosphere is not just hanging around the Sun but rather is exploding into space filling up the solar system and pulling with it the Sun's magnetic field known as the Inter-Planetary Magnetic Field or IMF.

Solar wind has a range of velocities. Bright areas of the Sun's surface produce slow solar winds due to the intense magnetic loops suppressing the solar winds. Whereas dark regions are where the magnetic field tends to be more radial. The charged particles move along these fields and those tend to be the source of fast solar winds.

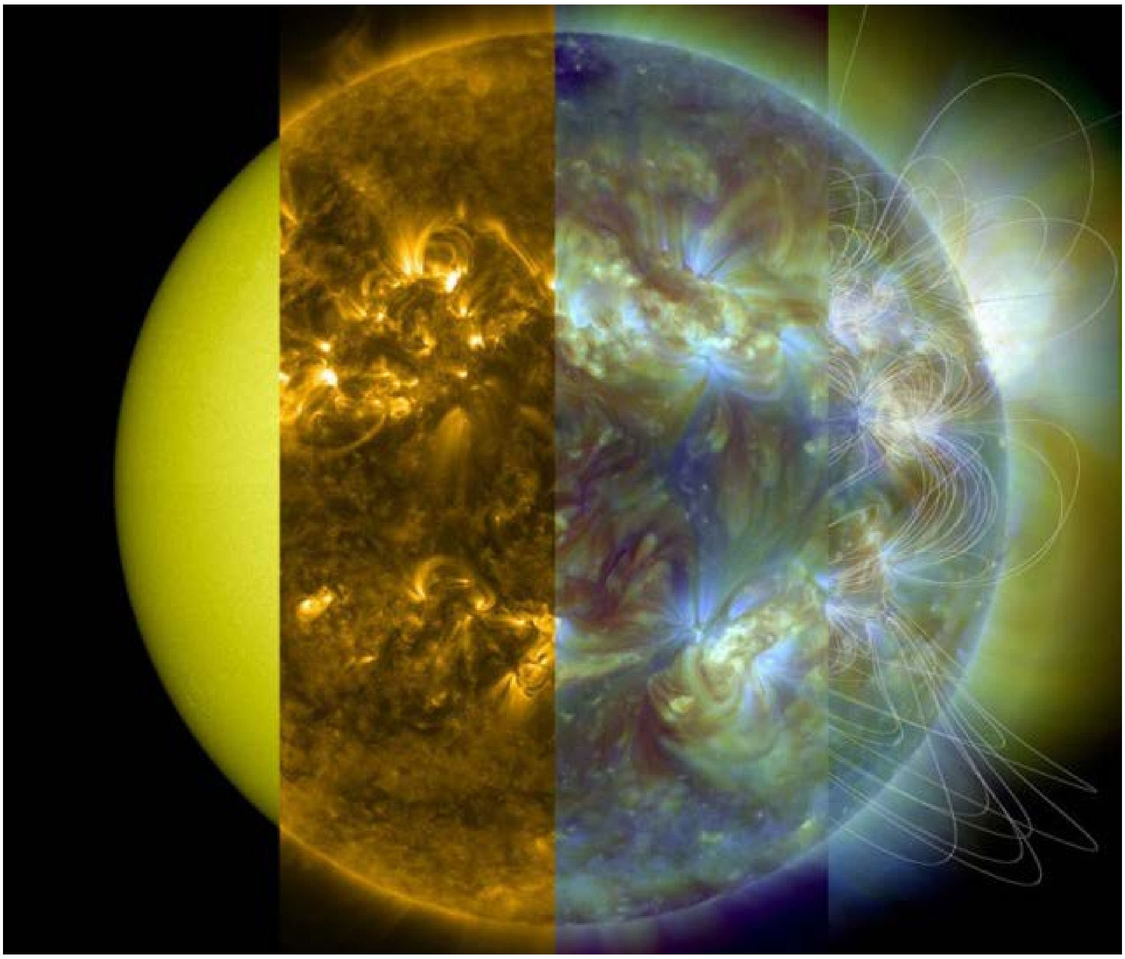


Figure 1: Visualisation of the layers of the Sun through various SDO data and metadata. Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

The types of ejections we can get from the sun include:

- When one of the intense magnetic loops becomes unstable, it creates an explosion of solar material delivering fast, dense, intense magnetic events. These explosions are called coronal mass ejections (CME) and create the biggest storms on Earth.
- High Speed Streams (HSS) and Co-rotating Interaction Region (CIR). As the Sun rotates the fast solar wind flow may overtake and compress a slow flow and create a step-like function which smacks the earth with medium strength and repeated storms.
- Solar flares which are flashes of x rays and solar energetic particles but these are not really relevant to geomagnetic disturbances.

The Earth acts as a rock in a stream to the solar wind; a magnetised rock with a very strong dipole field. When the solar wind hits this magnetic field it creates a bow shock as the solar plasma compresses against the Earth's magnetic field (Figure 2). Once this material reaches Earth it begins to transfer energy from the motion of the particles and the embedded magnetic field to the Earth's magnetic field and the Earth's atmosphere through a mechanism called Magnetic Reconnection. The Earth's magnetic fields is orientated north-south but the inter-planetary field can be in any direction and is quite variable. If it lines up southward, (southward IMF), it means it is oppositely directed to the Earth's magnetic field and will defuse across the boundary and start magnetosphere convection dumping energy in the Earth's magnetic system.

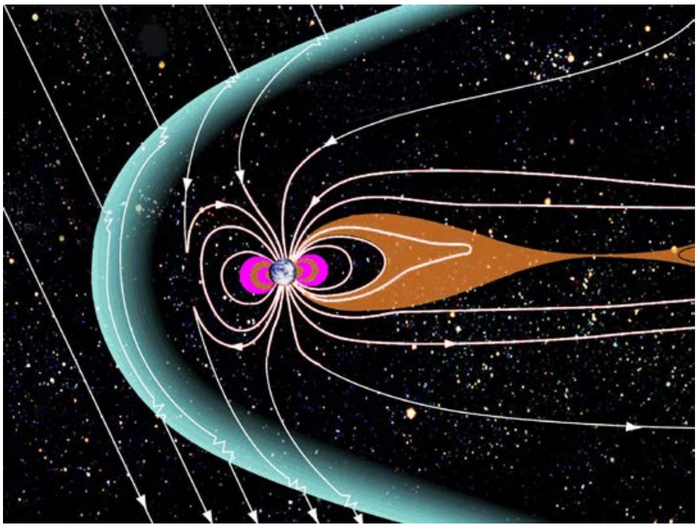


Figure 2: The Earth and IMF interaction

A big reservoir of this energy is called the ring current. During a southward IMF, plasma is driven in from the tail (night side of Earth), it's heated to kilo electron-volt energy levels and it begins to drift, ions one way electrons another, resulting in a ring or torus of electric current around the Earth's equator. This current produces an induced magnetic field that counteracts the Earth's surface dipole field. The corresponding decrease in the surface magnetic field strength is used to assess the severity of the magnetic storm via an index known as the storm-time disturbance index (Dst).

There is also the formation of magnetic field aligned currents, called Birkeland currents that close through the ionosphere near the poles creating Pedersen and Hall currents which are associated with the aurora (Figure 3). In general, geomagnetic storms are loosely defined by the intensification of the ring current, Birkeland currents and associated ionospheric currents and aurora. These events are very dynamic and have numerous transient phenomena, such as sub-storms, sudden impulses, or localized fast tail flows, which complicates the space environment.

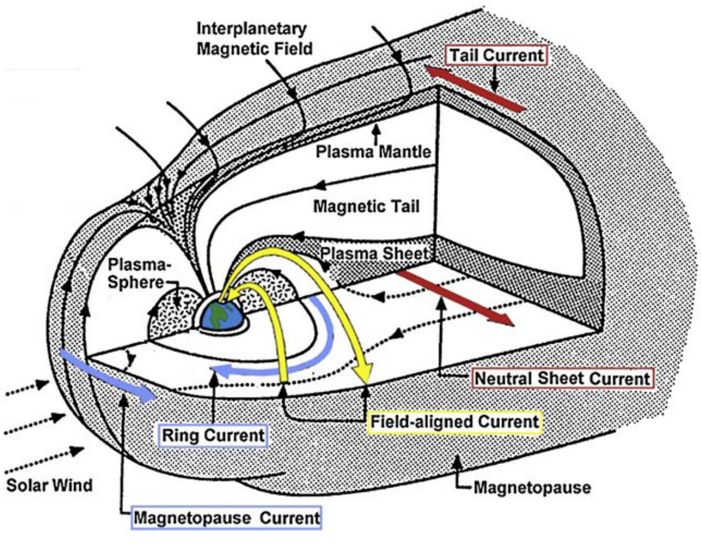


Figure 3: Schematic illustration of magnetospheric current systems contributing to the near-Earth magnetic field [6].

As a consequence of Faraday's law of induction, an electric field at the surface of the Earth is induced which is associated with the time variations of the magnetic field in the atmosphere. This field will induce a quasi-DC voltage in technological conductor networks. If these conductors are parts of a closed loop, e.g. neutral grounding of transformers at the ends of a high-voltage transmission line, a quasi-DC current will circulate by entering and exiting the power system through the neutral grounding of transformers (Figure 4). This current is known as a geomagnetic induced current (GIC) and has a range of frequency between 0.1 mHz-0.1 Hz, which is equivalent to waves with periods ranging from seconds to a few hours [7].

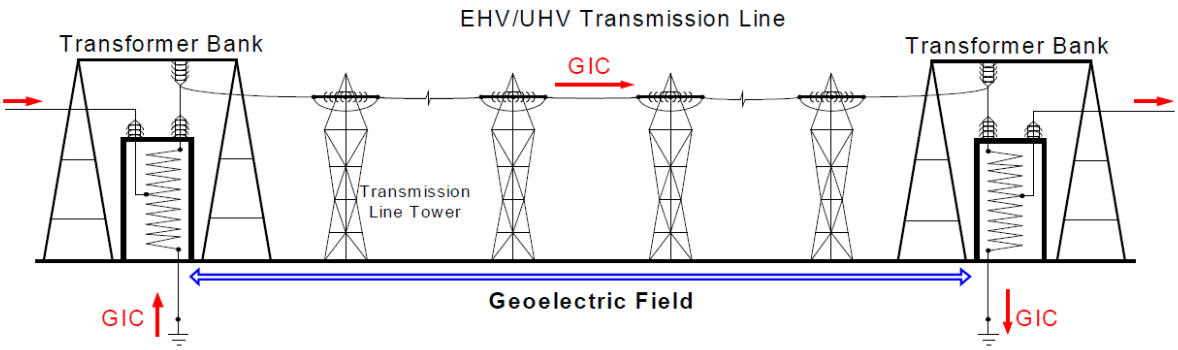
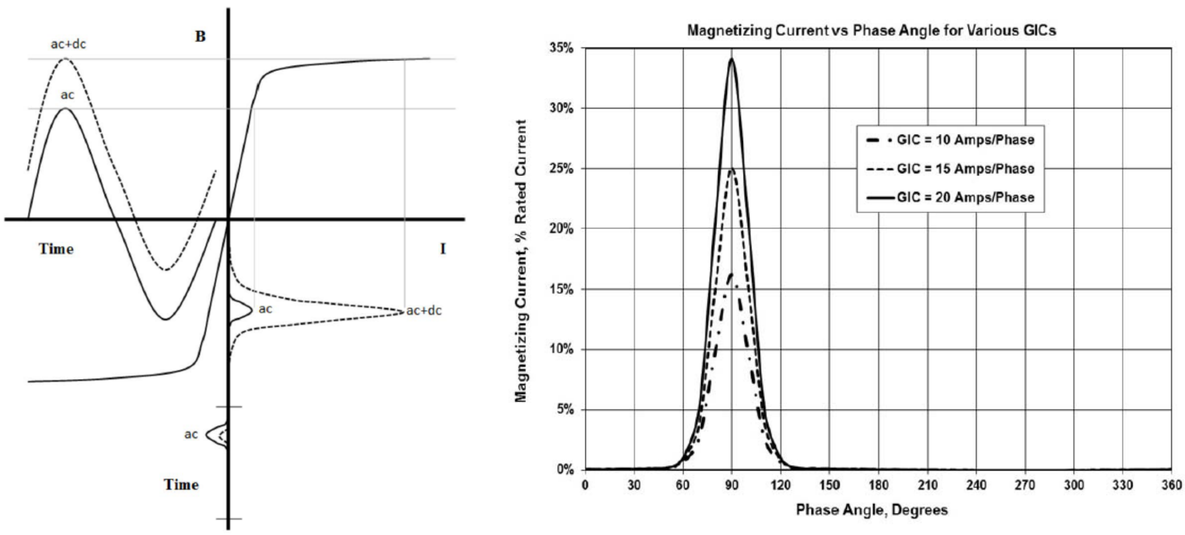


Figure 4: GIC flow in a power network [8].

The flow of GICs through power transformers is the root cause of nearly all geomagnetic disturbance (GMD) related issues [9]. It causes part-cycle saturation in power transformers (Figure 5), which can result in issues such as increased reactive power absorption, current harmonic generation, system voltage instability, and transformer heating and even failure (Figure 6).



(a) (b)

Figure 5: Effects of GICs on power transformer magnetising current [8]. (a) Part–cycle saturation of transformer cores under effect of dc. (b) Magnetizing current pulse for 3 different levels of GIC.

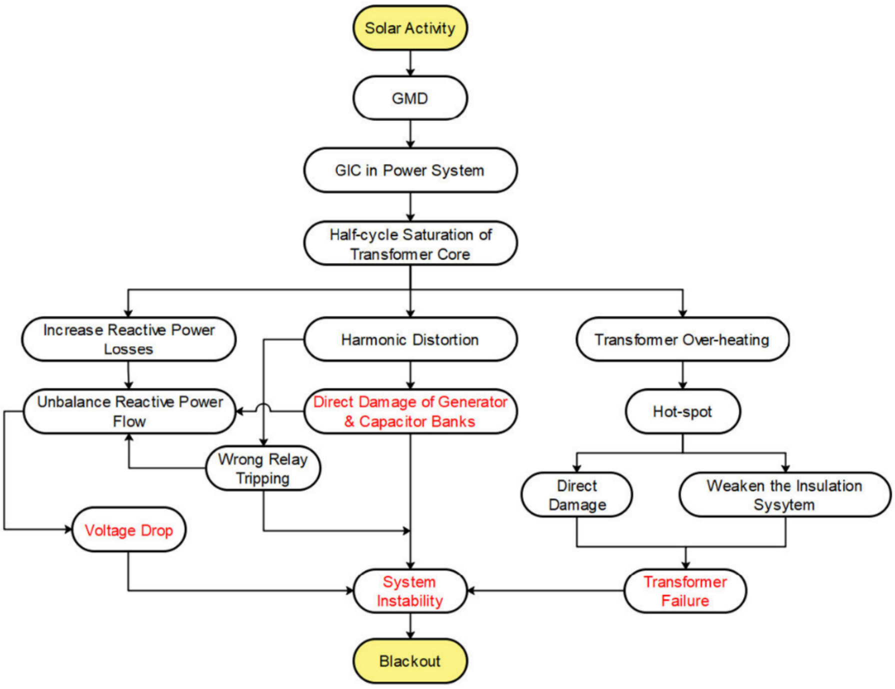


Figure 6: Overview of the GMD and GIC impacts on power systems and transformers [10].

There have been a number of notable space weather events throughout modern times as outlined in Table 1. The March 1989 event caused failure of the Quebec power grid [11] and damaged transformers in the United Kingdom [12]. In October 2003 a solar storm led to a blackout affecting 50,000 customers in Sweden [13]. One of the largest events on record is known as the “Carrington” event which occurred in 1859 and created auroras as close as 23° from the Earth’s equator [14]. If such an event were to happen today, we can expect to see GICs orders of magnitude larger than what is normally seen during a geomagnetic storm [15]. It also seems that storms the size of the Carrington event are indeed possible such as the July 2012 CME that narrowly missed Earth [16].

Table 1: Notable Space Weather Events [17].

Date	Comment
September 1859	The “Carrington” event is the benchmark for extreme space weather studies.[29–33] The solar flare, the geomagnetic storm, and the energetic particle flux associated with this event make it one of the largest on record.[30] Note that many crucial parameters were not measured directly, so its precise properties are subject to uncertainty. In particular, estimating the strength of the geomagnetic storm associated with the Carrington event has attracted some debate; initial estimates[34] should be disregarded in favor of more recent analysis.[35,36]
May 1921	This geomagnetic storm has been estimated to be comparable in size to the current best estimate of the Carrington event.[37,38] Auroras were seen near the equator in Samoa,[30] and geomagnetically induced currents (GICs) caused fires at several telegraph stations in Sweden.[39]
May 1967	An extreme solar flare and coronal mass ejection caused very significant radio blackouts, solar radiation storms, and a major geomagnetic storm. This caused a particularly significant disruption to communications, specifically to the military, and marked the start of a significant U.S. investment in space weather monitoring that continues to this day.[40]
March 1989	The largest geomagnetic storm of the space age[41] causing well-known failure of the Quebec power grid[42] and damaging two transformers in the United Kingdom.[43]
October–November 2003	Very well-observed and measured complex series of events including one of the largest observed solar flares on record.[44,45] The overall technological impact is extremely well documented.[46–49] A 90-minute blackout in 2003 affected 50,000 customers in Sweden. (Although it is now widely recognized that this blackout would probably have been avoided if current operational warning systems had been in place).[50]
July 2012	This CME was not Earth directed, but was measured *in situ* by the STEREO-A spacecraft.[51] If this CME had been Earth directed, it would have generated a very severe “Carrington class” geomagnetic storm.[52,53] It has been argued that this event should be used to create severe space weather scenarios for planning purposes.[52]

Most of the satellites observing solar winds are hanging out at the L1 Lagrange point (Wind, ACE, DSCOVR, and SOHO) while occasionally there are satellites closer to the sun which can measure things. L1 is about 1.5 million kilometres to Earth or about 45 minutes (or less) before solar winds reach Earth. Thus, most of our observations of the Sun are optical which can yield information about the polarity of the near-Sun magnetic field and information about CME launch trajectory. We also have coronagraphs which give the velocity and rough directions of CME propagations. We don't see the density, the strength of the magnetic field, and the plasma properties of the solar wind until it reaches L1. i.e. most forecasts give very little lead-time before an event.

3. OK, what are we going to do about it?

Led by Professor Craig Rodger (University of Otago) we are undertaking a 5 year research programme investigating space weather impacts on key infrastructure. Both Transpower Ltd and the nation's largest gas pipeline operator, First Gas Ltd, are partners in this research proposal. Independently, with major shared objectives, they have identified the most crucial issues for NZ in this field of hazard mitigation research. To address these knowledge gaps, the research team has developed a Research Plan comprising a set of interlocking work packages outlined below.

Work Package One: Geomagnetic Storm Impact on NZ

This work package, led by Dr Tanja Peterson (GNS), Assoc. Prof. Ting Wang (UO) and Dr Dan Welling (UTA) is about determining the likelihood and properties of extreme geomagnetic storms at the 1 in 100 to 200 year level. They plan to undertake this by:

1. Statistical analysis of historic Eyrewell Geomagnetic Observatory (EYR) magnetic field observations. Currently there are daily magnetograms (paper records) from 1916 (Amberly) to 1995 (Eyrewell) with digital data for Eyrewell since 1990. That's about 74 years of historical data to retrieve (~27,000 magnetograms). Once digitised, these records will aid developing statistical models to determine the likelihood of future events.
2. Using physics models to predict the impact of extreme storms. Extreme storm modelling from the Michigan Model, National Oceanic and Atmospheric Administration (NOAA) data and the Space Weather Modeling Framework (SWMF), a flexible software framework for executing, synchronizing, and coupling models of the space environment.

This information will help with creating a business case cost-benefit analysis and working out what the extreme storm impact will be.

Work Package Two: Electrical Resistivity Structure NZ

Our proposed research requires knowledge of the electrical conductivity of the ground and subsurface structure. As New Zealand is geologically young and active, this is complex and varying. This will be addressed in this work package, by using a combination of historic magnetotelluric (MT) observations along with new MT surveys, undertaken in Southland and Northland, aimed to fill gaps in crucial regions. This work package is led by Dr Wiebke Heise (GNS), Dr Ted Bertrand (GNS), and Dr Malcolm Ingham (VUW).

This work package is needed for modelling extreme storm impacts, especially in the lower South Island and upper North Island where MT data is lacking.

Work Package Three: Predicting Changing Magnetic Field

In Work Package Three, Prof Craig Rodger (UO), Dr Alan Thomson (BGS) and Dr Dan Welling (UTA) will be investigating how to predict the changing magnetic field across NZ during geomagnetic disturbances. This will be investigated experimentally and through modelling. Multiple magnetometers and variometers will be installed across NZ to improve the spatial variation. Physical models of solar wind-magnetosphere interactions through the Michigen Model/SWMF will be improved for the specific needs of our mid-latitude/Southern Hemisphere location.

This work is needed for modelling extreme storm impacts, especially in the lower South Island and upper North Island where MT data is lacking.

Work Package Four: A 3-D NZ GIC Physics-Based Model

Prof Craig Rodger, Dr Mikhail Kruglyakov, and Daniel MacManus (UO), Prof Alexey Kuvshinov (ETH), and Mike Dalzell (Transpower) will be getting the best modelling representation they can for existing geomagnetic disturbances for NZ and validate it from Transpower GIC data (and maybe some pipeline data eventually). This work package will incorporate information from Work Packages 2 and 3. It is needed for making a validated model we can use to determine extreme storm impacts for NZ energy systems.

Work Package Five: Forecasting and Nowcasting Tools for NZ

In this work package, we aim to develop forecasting and nowcasting tools to provide high-quality information to energy operators to allow informed decisions by:

1. piping near real time magnetometer data to energy operators (i.e., Transpower control room).
2. Testing operational NOAA SWPC predictive models in an NZ context.
3. Probabilistic forecasting examination from solar wind.

This is needed for delivering nowcasting tools to the control room and finding a route by which NZ has confidence in space weather predictions (from NOAA SWPC). This work package will be led by Prof Craig Rodger and Assoc. Prof. Ting Wang (UO), Dr Tanja Peterson (GNS) and Dr Howard Singer (SWPC).

Work Package Six: Incremental Impact of Geomagnetic Storms

There is evidence that the effect of GIC on transformers is cumulative, which would impact a transformers ability to cope with large short-lived events. In this work package, Dr Andrew Lapthorn (UC), Mike Dalzell (Transpower), Dr Alan Thomson (BGS), Dr David Boteler (SWC), and Dr Mark A. Clilverd (BAS) will examine this phenomena through:

1. Dissolved gas analysis and other diagnostic measurements to seek evidence of stress/damage after geomagnetic disturbances.

2. Active experimental campaigns injecting DC (from the HVDC link) into Haywards transformers

This work package is needed to work out if it is true or not that small storms cause cumulative damage and to test in a controlled way the impact of GIC in an operational transformer.

Work Package Seven: Impact on Gas Pipelines

By coupling the work from work packages 1 and 4 (validated extreme storm modelling) to the NZ gas pipeline network. Malcolm Ingham (VUW), Mark Sigley (FirstGas), Prof Craig Rodger and Dr Mikhail Kruglyakov (UO), and Dr Gemma Richardson and Dr Alan Thomson (BGS) will use First Gas measurements to validate the pipeline model.

This work is needed for determining the hazard to natural gas pipeline networks from extreme geomagnetic disturbances - and thinking about possible mitigation approaches.

Work Package Eight: Maximising Public Awareness

Work package eight focuses on outreach activity and is led by Craig Grant from Otago Museum. While our outreach activity will involve public talks, it is much wider and deeper. The outreach work package will involve dedicated Mātauranga Māori engagement and outreach programme with iwi and hapu partners. This work will leave the country better able to understand the science involved so they can better adapt to the risks and will enable communities to maximise the social and economic benefits from aurora.

4. Conclusions

The threat to infrastructure, such as communications and electric power, from large solar storms or solar tsunamis is very real and can potentially cause significant economic and societal damage on a global scale. Large storms have reached Earth in the past and evidence suggests it will happen again. Furthermore, with current technology we potentially have very little warning of a storm’s impact before it hits. However, with the right preparation and knowledge we can put systems and processes in place to protect key assets from potential damage but we do need to act. A “do nothing” approach will inevitably end in significant damage on a wide scale. We are now undertaking a 5-year, government-funded, research program over multiple institutions both in New Zealand and internationally to ascertain what the potential impacts of large solar storms are, how likely they are to occur and what plans we’ll need to have in place to ensure the safe operation of these key assets.

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